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# The interplay between cosmic rays and magnetic turbulence in galaxy clusters: radio halos and $\gamma$ -rays

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## Abstract

The interaction of magnetic turbulence and relativistic particles is a important process for understanding particles propagation and acceleration in many astrophysical environments. Large-scale turbulence can be generated in the intra-cluster-medium (ICM) during mergers between galaxy clusters and affects their non-thermal properties. Giant radio halos, Mpc-scale synchrotron sources observed in merging clusters, may probe the connection between turbulence and non-thermal cluster-scale emission. After discussing relevant aspects of the physics of turbulence and turbulent acceleration in the ICM, I will focus on recent advances in the modeling of non-thermal emission from galaxy clusters.

## 1 Introduction

Clusters of galaxies and filaments are the largest structures in the present universe in which the gravitational force due to dark matter overcomes the expansion of the universe. Baryonic matter in clusters is heated to roughly the virial temperature, but there is room to accommodate a non negligible amount of non-thermal energy in the form of accelerated particles. Indeed clusters are expected to be sites of acceleration and storage of charged particles and sources of non-thermal radiation from radio to  $\gamma$ -rays (Blasi et al 2007 for review).

This theoretical picture is supported by radio observations that indeed show the presence of diffuse synchrotron radiation on Mpc scales in a fraction of massive and nearby galaxy clusters. The radio emission is due to relativistic electrons, with energies several GeV, diffusing in  $\mu$ G magnetic fields and it is classified as *radio halos*, roundish low brightness sources from cluster central regions, and *radio relics*, elongated sources typically found in the clusters outskirts (e.g., Ferrari et al. 2008 for review). Giant radio halos are the most spectacular and best studied cluster-scale non-thermal sources. Limits on their polarization (at few percent level) and their morphological similarity with the cluster X-ray emission suggest that the radio emission is generated from the same regions where X-rays are produced, and that the relativistic plasma is mixed with the thermal one. Radio observations and their follow up in the X-rays show that giant radio halos are always found in merging systems while they are not generated in more relaxed clusters, suggesting that a fraction of the gravitational energy that is dissipated during merger events is channelled into the generation of non-thermal components (eg. Cassano et al. 2010 and ref therein).

Two important mechanisms may play a role for the origin of radio halos: the generation of secondary electrons from inelastic collisions between relativistic and thermal protons (pp) in the ICM (eg., Blasi & Colafrancesco 1999, Pfrommer & Enßlin 2004, Keshet & Loeb 2010), and the (re)acceleration of primary and/or secondary particles in the ICM due to turbulence

generated during cluster mergers (eg. Brunetti et al 2001, Petrosian 2001, Brunetti & Blasi 2005). Turbulent reacceleration may naturally explain the connection between halos and cluster mergers and became a popular scenario for the origin of radio halos. Most important the synchrotron spectrum of a number of radio halos shows a curvature at higher frequencies (or it is very steep) suggesting that the mechanisms responsible for the acceleration of electrons in the emitting  $Mpc^3$ -regions are poorly efficient, with acceleration time  $\tau_{acc} \sim 10^8$  yrs, consistent with acceleration by turbulence (Schlickeiser et al 1987, Brunetti et al 2008).

In this contribution I will focus on relevant aspects of turbulence and particle acceleration by magnetic turbulence in the ICM and on the clusters spectral energy distribution expected from models of turbulent acceleration of primary and secondary particles.

## 2 Turbulence in galaxy clusters

A simple estimate of the Reynolds number in the ICM gives  $\mathcal{R} \sim 10^2$  which is barely sufficient to initiate turbulence. This value however significantly increases if the effect of the ICM-magnetic field (mean and rms) on the particle mean free path (and viscosity) is taken into account, suggesting that the ICM is turbulent at some level (eg., Subramanian et al 2006, Brunetti & Lazarian 2007). The properties of turbulence in galaxy clusters are discussed in many review papers (eg Lazarian & Brunetti 2011 for recent review), in the following I will briefly describe few observational and theoretical aspects.

Limits to the turbulent velocity support in the cores of cool-core clusters have been recently obtained through X-ray spectroscopic observations, they constrain the energy of turbulent motions on 10-30 kpc scales at  $\sim 10 - 20\%$  of the thermal energy budget (Sanders et al 2011). Analysis of the pressure fluctuations in the cores of a few galaxy clusters agree on the possibility of a substantial pressure support from turbulent motions, of the order of 10% of the thermal pressure (eg., Churazov et al 2011 and ref therein). Direct evidence of turbulent motions in the ICM come from the analysis of the Faraday Rotation (RM) of the polarised emission from cluster and background radio sources. The magnetic field topology inferred by these studies is turbulent with coherent scales ranging from a few kpc to several ten of kpc (Bonafede et al 2010 and ref therein).

The generation of turbulent motions on large scales in galaxy clusters is a unavoidable byproduct of the hierarchical process of cluster formation (eg Iapichino et al 2008, Ryu et al. 2008, Vazza et al 2011). Numerical simulations suggest that turbulence is produced mainly by merger-induced shear flows and that in the case of merging clusters it may contribute up to 10-30% of the total thermal energy budget. Large-scale turbulent motions, injected at scales  $L_o \sim 100 - 500$  kpc during mergers, are important drivers of turbulence at smaller scales. We expect typical velocities of the turbulent eddies at large scales  $\delta V_{L_o} \sim 300 - 700$  km/s which makes turbulence sub-sonic, but strongly super-Alfvénic ( $\delta V_{L_o} \gg V_A$ ,  $V_A$  the Alfvén velocity in the ICM). Turbulence at large scales is thus essentially hydrodynamic and made of compressive and incompressive eddies. Under these conditions lines of the mean field in the ICM are tangled and stirred by motions resulting in a complex topology of the ICM-field, in line with observations of RM. Viscosity in a turbulent and magnetised ICM is strongly suppressed due to the effect of the bending of magnetic field lines and of the perturbations of the magnetic field at small scales induced by plasma instabilities. The important consequence is that turbulence is expected to establish a inertial range down to small scales. In the inertial range the velocity of turbulent eddies decreases with scales and becomes sub-Alfvénic, at these scales the properties of magnetic turbulence in the ICM should be similar to those of

MHD turbulence.

At small scales the ICM becomes collisionless and additional physics comes into play. The non-linear coupling between turbulent and particles drains a fraction of turbulent energy into particle heating and acceleration. In the classical formulation the ICM becomes collisionless at scales  $\leq$  the Coulomb scale  $\sim 10$  kpc. However the effective mean free path in a turbulent plasma may be determined by other complex effects, for example by the scattering with magnetic field perturbations generated by plasma instabilities. Although this territory is still poorly explored, we might reasonably claim that the ICM “behaves” collisional at scales significantly smaller than the classical Coulomb scale (Brunetti & Lazarian 2011a). The generation of plasma instabilities due to the coupling between turbulent modes and thermal and relativistic particles is expected to back react on the turbulent spectrum generating waves at small scales. This provides a elegant mechanism, complementary to turbulent cascading, to transport turbulent energy from large to very small scales (eg. Yan & Lazarian 2011).

### 3 Particle acceleration by magnetic turbulence

Charged particles in magnetic turbulence are accelerated stochastically by interacting with electric and magnetic field fluctuations (eg. Melrose 1980 for review). The condition for resonant interaction between a particle with momentum  $p$  and a wave with frequency  $\omega$  and wavenumber  $k$  is  $\omega = k_{\parallel}v_{\parallel} + n\Omega/\gamma$  ( $k_{\parallel}$  and  $v_{\parallel}$  are the wavenumber and particle-velocity components along the mean magnetic field), where  $n = \pm 1, 2, \dots$  give gyroresonance with electric field fluctuation. The case  $n = 0$  marks Transit-Time-Damping (TTD), a coupling between the particle magnetic-momentum and the magnetic (turbulent) parallel gradients. Acceleration of electrons from the thermal pool to relativistic energies by MHD turbulence in the ICM faces serious problems due to energy arguments (eg. Petrosian & East 2008). Consequently, turbulent acceleration models must assume a pre-existing population of relativistic particles that provides the seeds to reaccelerate during cluster mergers (eg. Brunetti 2011 for review). A correct description of the process of reacceleration of seed particles is challenging. It requires taking into account the fundamental properties of magnetic turbulence as well as the mutual feedback of magnetic fields and energetic particles in the turbulent medium. The last decade has been marked by substantial advances in understanding of magnetic turbulence in the MHD regime that provides a solid “guide” to model turbulence in galaxy clusters across a fairly large range of spatial scales. At collisionless scales the collisionless interaction of turbulent perturbations with thermal and non-thermal particles changes the turbulent spectrum with time since dampings transfer turbulent energy into particles, this in turn affects (self regulates) also the efficiency of the particle acceleration process. The picture becomes more challenging when additional processes, such as plasma instabilities, are considered. A variety of instabilities (e.g. firehose, mirror, gyroresonance etc) can be generated in the ICM in the presence of turbulence, they can lead to the transfer of energy from large-scale turbulence to perturbations on smaller scales and may play a role in the process of scattering and acceleration of relativistic particles. A satisfactory modeling of the particle acceleration process by magnetic turbulence in galaxy clusters would require taking into account self-consistently all these mechanisms, which is a challenging territory for future studies. Yet substantial steps in the modeling of turbulent acceleration in galaxy clusters lead to conclude that it is an important process to explain the phenomenology of non-thermal emission from cluster-scale.

In Brunetti & Lazarian (2007) we considered the advances in the theory of MHD turbulence to develop a comprehensive picture of turbulence in the ICM and to study the reac-

celeration of relativistic particles by compressive turbulence by considering all the relevant collisionless damping processes. According to our approach large scale turbulence, generated in the ICM during cluster mergers, cascades at smaller (collisionless) scales where turbulent waves can interact non-linearly with relativistic and thermal particles. Under the hypothesis that the collisionless scale of the ICM is  $\sim$ Coulomb ion mean free path, particle acceleration is mainly due to fast modes. The most important collisionless damping of these modes in the hot ICM is the TTD resonance with thermal particles that essentially transfers turbulent energy into heating of the thermal ICM. In this case it is calculated that only  $\sim 10\%$  of the energy of compressible turbulence goes into the (re)acceleration of seed relativistic particles via TTD. This scenario allows prompt calculations of particle acceleration by MHD turbulence in the ICM. The ensuing cluster-scale radio emission generated in merging clusters results in very good agreement with present observations of radio halos.

In other physical situations a larger fraction of the turbulent energy can be dissipated into the (re)acceleration of seed relativistic particles in galaxy clusters. This is the case of the gyro-resonant interaction with Alfvén modes at small scales that has been considered in several papers that attempt modeling radio halos (e.g. Ohno et al 2002, Fujita et al. 2003, Brunetti et al. 2004). A large fraction of the energy of compressible turbulence can also be transferred to relativistic particles by TTD with fast modes under the assumption that the ICM "behaves" collisional at scales much smaller than the Coulomb ion mean free path (e.g. Brunetti & Lazarian 2011a). In all these cases where a large fraction of turbulent energy is channeled in the reacceleration of relativistic particles the efficiency of the particle acceleration process is self-regulated by the back-reaction (damping) of particles on the spectrum of turbulence. Stronger turbulence induces more efficient acceleration leading to a faster growth of the particles energy density with time. This – however – increases the damping of turbulence and the interaction approaches a quasi-asymptotic (and very complex) regime where relativistic particles get in (quasi) equipartition with turbulence and self-regulate their (re)acceleration.

## 4 Turbulent (re)acceleration of primary and secondary particles

Cosmic ray protons in the ICM are long-living particles that can be confined (and accumulated) in clusters (Völk et al 1996, Berezinsky et al 1997) with the unavoidable generation of secondary particles in the ICM. Secondary electrons provide a natural reservoir of seed particles that can be reaccelerated by interacting with magnetic turbulence in galaxy clusters. In Brunetti & Lazarian (2011b) we model self-consistently the interaction of compressible turbulence and relativistic protons and their secondaries generated in the ICM.

This general scenario predicts that galaxy clusters are non-thermal sources from radio to  $\gamma$ -rays. The gamma-ray emission is mainly due to decay of  $\pi^0$  generated from pp collisions in the ICM and it does not (strongly) depend on cluster dynamics. The level of radio emission from these models is tightly connected with the dynamical properties of the hosting clusters. Magnetic turbulence in merging clusters reaccelerates secondary electrons generated from pp collisions resulting in enhanced "on state" synchrotron emission in the form of giant radio halos. The scenario leads to the unavoidable expectation of "off-state" radio halos in relaxed systems, namely Mpc-scale emission generated by the continuous injection of secondary electrons in the ICM. Calculations predict a luminosity of "off-state" halos in more relaxed systems roughly one order of magnitude smaller than that of "on state" radio halos, a possibility that can be tested with deep radio surveys (Brown et al 2011).

Figure 1 shows the expected spectrum in the case of the Coma cluster where the energy

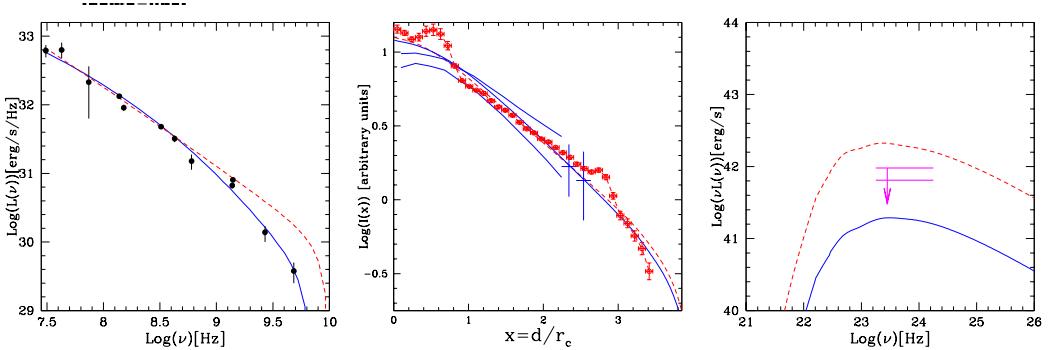


Figure 1: Synchrotron spectrum (left) and brightness profile (central panel; the radial distance is in units of core radius, red points and blue data are from 325 MHz observations) of the Coma radio halo, and the cluster  $\gamma$ -ray spectrum from  $\pi^0$ -decay (right; the  $2 - \sigma$  FERMI upper limit is from Ackerman et al 2010, we also show the FERMI sensitivity expected after 3.5 years). We show the case of turbulent reacceleration (solid-blue) and pure-secondary (dashed-red) models. We assume a scaling between relativistic and thermal protons energy-densities  $\epsilon_{CR} \propto \epsilon_{TH}^{1-f}$  with  $f = 1.15$  and  $1.5$  for reacceleration and secondary model, respectively. Following best fit from RM (Bonafede et al 2010) the magnetic field energy density is scaled with the thermal energy density and the central field value is  $= 4.7\mu\text{G}$ .

content of compressible turbulence is assumed  $\approx 18\%$  of the ICM and the energy density of the reaccelerated relativistic protons is  $\sim 4\%$  of the ICM. The model provides a very good agreement with both the synchrotron spectrum and radio brightness distribution of the radio halo (see caption for details). Gamma ray emission is expected from the Coma cluster at  $\sim 10 - 20\%$  level of present upper limits from FERMI. In Fig.1 we also show model results where “no” turbulence is assumed. Under this condition radio emission is maintained only by the process of continuous injection of secondary electrons from pp collisions. In this case however to explain the radio luminosity and brightness profile of the Coma halo it is necessary to assume a large energy content of primary relativistic protons, about 10 times larger than in the previous case. The drawback of this scenario is a  $\gamma$ -ray emission from  $\pi^0$  decay that is larger than present limit. This suggests that the mechanism of generation of secondary particles via pp collisions in the ICM (secondary models), when considered alone, is not sufficient to explain radio halos, unless the cluster magnetic field is substantially larger than that derived from RM (Brunetti et al in prep).

## 5 Conclusions

Giant radio halos are probes of complex mechanisms of particle acceleration in turbulent ICM-regions. Substantial advances in understanding stochastic particle acceleration by magnetic turbulence in galaxy clusters have been achieved by using physically motivated models of turbulence and by considering the reacceleration of both primary and secondary particles in the ICM. These studies suggest that turbulent acceleration is a important process to understand the phenomenology of radio halos and their connection with cluster mergers. The lack of detections of galaxy clusters in the  $\gamma$ -rays provides additional constraints to the nature

of radio halos. Turbulent reacceleration models are consistent with the radio properties of the Coma halo and with the present FERMI upper limit. On the other hand the brightness profile of the radio halo would imply a  $\gamma$ -ray luminosity that is appreciably larger than the FERMI limit assuming pure secondary models; in order to reconcile secondary models with radio and  $\gamma$ -ray observations the magnetic energy density in the Coma cluster must be postulated 5-10 times larger than that constrained from RM.

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